Electric Propulsion Power System - Overview

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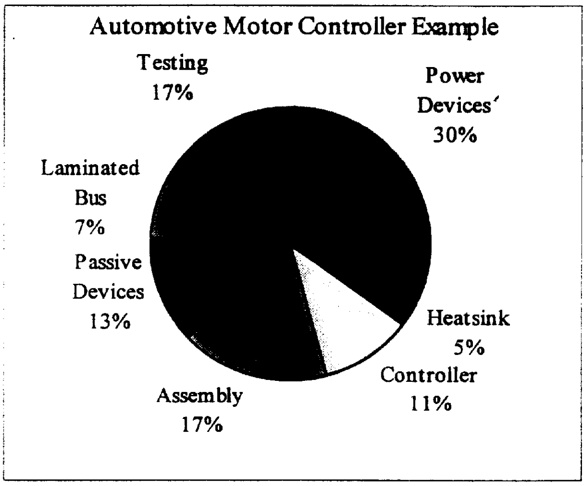
Brief History of Power Electronics

Electric vehicles were first produced around the turn of the century. These first electric automobiles were powered by lead acid batteries and direct current motors. By the 1930's, advances in internal combustion engines, coupled with the low cost of gasoline, had quickly pushed electric vehicles out of the consumer market. The economic Oil Shocks of 1970's resulted in renewed interest in electric vehicles, and prompted the United States Congress to enact The Electric and Hybrid Vehicle Act in 1976. However, electric power system technology has not improved substantially beyond what it was in the 1930's. The Act's research and development efforts have focused on technologies to reduce costs and to improve system performance through programs like the U.S. Automotive Battery Consortium (USABC). Despite renewed interest and increased research and development efforts, the problems of high cost, low reliability, and availability of power electronic components still remain.

Projection of Costs Through 2005 and 2015

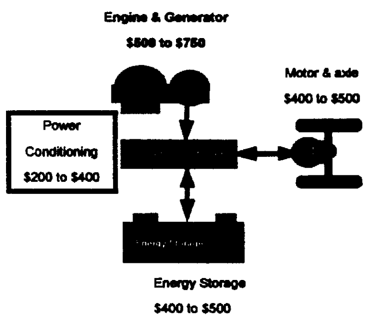
Today's transportation power systems are expensive; typically \$2500 to \$3500 for a propulsion system. These costs are expected to fall to about \$1500 for production of mass quantities using conventional construction methods. The costs break into several main areas; filters make up about 10% to 20% of the system cost, the switches 30% to 40%, controls 10%, about 20% for hardware and with testing and labor cost making up the balance.



The state-of-the-art in power electronics today for hybrid vehicles is akin to making a desktop computer from discrete components. Clearly what is needed, is improved integrated power technology that has process driven versus inspection driven quality control, and advanced materials to meet the demands of automotive applications.

Cost Analysis

- Projections for a 100 kW motor controller is about \$2500
- The entire propulsion system for a commercial auto is ~ \$2500
- Technology must improve!



Power Electronic Building Blocks Meet the Challenge

Power Electronic Building Blocks (PEBBs) are designed to meet the power electronic requirements for the advancing "Electric Age". The PEBB is an integrated power device that imposes a paradigm shift on the electric power industry similar to the shift from transistors to integrated circuits. The paradigm shift in power electronics will place device design at the semiconductor factory, allowing the applications house to concentrate on system design. A simplified PEBB cost projection is shown below based on a three phase bi-directional module and Semitech dynamic random access memory (DRAM) cost figures. Passive devices are considered exterior to the module, but could be integrated in the future.

Silicon Parts Estimate for a 1000 volt 600 amp Three Phase Hybrid Controller

Silicon parts	Qty.	Unit Cost 1998-2000	Extended Cost	Cost Est. for 2005	Extended Cost
Switches	6	$10.00	$60.00	$5.00	$30.00
Diodes	6	$10.00	$60.00	$5.00	$30.00
Package	1	$10.00	$10.00	$5.00	$5.00
Gate drive/control/memory	1	$25.00	$25.00	$20.00	$20.00
Sensors/AtoD	1	$25.00	$25.00	$10.00	$10.00
Assembly	1	$15.00	$15.00	$10.00	$10.00
Profit/R&D (50%)		$97.50	$97.50	$52.50	$52.50
Total:			$292.50		$157.50

Automotive needs and DOD demands are leading the charge, but many commercial applications will also benefit. Some of these spin-offs include variable speed motor controllers for air conditioners and industrial processes, "Smart Home" applications, and utility power factor controllers.

Power Electronics and Controls

A whole new class of electronic technologies is expected to emerge, spurred by the development of electric drive vehicles. The Department of Commerce estimates that by the year 2000, the content of electronic components in automobiles (e.g., sensors, transducers, semiconductors) will increase 200% from 1987 levels. Average dollar volume of electronics per U.S. passenger vehicle (excluding entertainment systems) has been tripling every 10 years, to about $1000 in 1990. Vehicle electronics have progressed from replacement of mechanical systems to features solely realized through interacting electronic controls. The 1990s will see electronics used in integrated powertrain controls, integrated chassis system controls, multiplexing, crash-avoidance systems, navigation, and communications.

The advent of the hybrid vehicle and technologies developed within the Partnership for a New Generation of Vehicles (PNGV) will further accelerate these trends. An electric powertrain and increased electronic engine controls will necessitate more complex sensing and power electronic control devices with faster semiconductor chip operation, increased input/output (I/O) pins, higher power density, and more power dissipation per device. Power semiconductor science and technology are critical to the future of electric drive systems. A quote from GM's Hybrid Vehicle program places the need for cost improvement in perspective: "$100 per switch [today's volume cost for a 600 amp/600 volt IGBT] is too high ...We need to get the price of power switches below $5.00 per switch to have a competitive product." In March of this year, the Vice President's fifth PNGV Symposium was focused on the issues related to vehicle electronics. The Power Electronics team concentrated on ways to produce a common 1996 baseline for a 100 kW traction motor controller and how to reduce cost by 50% in 1998 and 75% in 2000. GM, Ford, Chrysler, SATCON, Selectria, Westinghouse, Motorola, Harris Semiconductor, university and Government representatives attended.

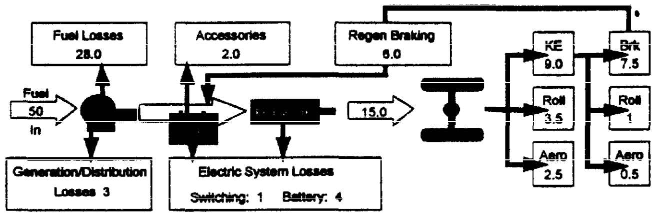
The increasing number of power conditioning subsystems in a hybrid vehicle is an area of concern. The hybrid vehicle has many nonlinear power switch networks interfacing with the generator, the storage system, the traction motor, and the accessory loads. Research at the University of Wisconsin at Madison, has shown that this type of operation can lead to unstable systems. In short, the nonlinear subsystems can be confused by each other's power switching signature. Working with industry and academia, the Navy/DOE PEBB program is designed to mitigate this concern.

Electric Vehicle

The electric vehicle has the simplest form of electric propulsion. The system consists of an energy storage device like a battery, a bi-directional converter or inverter powering a DC or AC motor, and smaller, but similar converters and inverters to power the accessories. The figure below shows a typical power distribution configuration, and associated losses, for an electric vehicle using chemical batteries for energy storage. The electric system losses account for the chemical inefficiency in a battery and the propulsion controller losses which are mainly due to the power switches. The electric utility is shown in the figure to illustrate its effect on the system efficiency.

Hybrid Vehicle

Electric Vehicle System Energy Use on an Urban Driving Cycle



The Hybrid Vehicle is more complex than the electric vehicle because it brings a "low emissions electric power unit" on-board, in place of the utility power grid and a large battery. The combination of an electric generator and a storage element provides the energy and power "feel" with which the customer is familiar, leading to greater customer acceptance. Near term candidates for the power unit are diesel cycle generators, turbine generators and Stirling cycle generators. These power units are designed to operate over a tight emissions band with high efficiency. Cleanly generated on-board electric power reduces requirements for a storage element, which may reduce vehicle weight and overall system costs.

Fuel Cell Vehicle

A fuel cell is an electrochemical energy conversion device which uses a hydrogen-rich fuel (supplied either as direct hydrogen or as a reformed fuel). The hydrogen ions travel across a membrane to react with oxygen from air to reproduce electricity, water and heat. The fuel cell does not "burn" its fuel and therefore has very low emissions. Fuel cell powered vehicles will be, cleaner, and quieter than today's cars.

There are five major types of fuel cells; alkaline systems, phosphoric acid systems, proton exchange membrane (PEM) systems, solid oxide systems and molten carbonate systems. PEM fuel cells operate at the lowest temperatures, approximately 80° C which allows quicker startup, and have the highest near term potential for high power density at low cost. PEM fuel cells are the most likely for near-term automotive applications.

Thermo-Electric Powered Vehicle

Like the fuel cell, thermoelectric power plant-equipped vehicles are hybrid vehicles. Thermoelectric power units promise a simple and versatile solution; the power plants convert heat energy directly to electricity. Since the energy conversion is independent of the heat source, they offer a high potential for environmentally friendly power units. Many thermoelectric devices have a reversible cycle to serve as solid state air conditioning systems as well.

Seebeck devices are commercially available; they achieve only about 6% efficiency commercially and about 11% efficiency in the laboratory. Three other technologies show more promise; thermo-photovoltaics, quantum well devices and thermionic devices. Thermo-photovoltaics work similar to solar cells except that they work in the infrared region. Laboratory tests using a natural gas burner and selective optical emitters to improve performance have achieved 34 percent efficiency. Quantum well devices are nanostructures that trap photons in "energy wells." The energy absorbed by the photon can free an electron and make it available to an electric circuit. Quantum well devices demonstrate near linear efficiency characteristics with temperature and have achieved 40% efficiency in the lab with a 1000° C temperature differential. Thermionic emitters work like the hot cathode in a vacuum tube. The cathode emits electrons when it is heated, the electrons collect on a plate and produce a differential voltage. The differential voltage is only about 0.5 volt. Large systems like those employed on the Topaz space reactor only developed 11% efficiency. Vacuum microelectronics techniques have been applied to thermionics and promise to increase efficiency to approximately 50%. Vacuum microelectronics are nanostructure vacuum tubes developed for advanced thin display technology and gigahertz range frequency amplifiers. This structure is easily modified to become a nanoscale thermoelectric generator virtually eliminating the low voltage limitation.

The main issue for power units in the automobile market is cost. A complete integrated power plant needs to reach below three cents ($0.03) per watt.

Description of Power Electronic Systems and Components

This section focuses on the "glue" of an electric drive system; the components that connect and control system power between input and output. These distribution components are a major cost driver in electric systems today and could be a "show stopper" to the U.S. "More Electric" initiative without improvement. Fortunately this technology is moving toward a new generation of integration. Following their cousins in the computer world, and moving from discrete components to integrated circuits, will provide more convenience and power at a lower cost.

Converters & Inverters

Converters match the DC voltage level of a subsystem, like the fuel cell, battery or capacitor to the DC voltage level of the system voltage. These converters generally consist of an input filter, a chopper section with boost or buck circuits and an output filter.

Inverters create AC power for motors and actuators like the propulsion motor, a heat-pump compressor, or a power steering actuator. Inverters have an input filter, a switch network, and a simple output filter.

Different waveforms like sine waves, triangles or other waves are created by controlling the switching patterns of the six individual switches and smooth the waveform with the output filter.

A special class of inverters called the "soft switching" inverters, uses additional small switches to momentarily zero the voltage or current through the main switches to eliminate their switching loss. This is important because filter costs and harmonic distortion can be reduced when the switching frequency is increased. However, switching losses increase with switching speed. Soft switching permits high speed switching by removing this loss and the switch runs cooler and lasts longer. New soft switching topologies will marginally increase the switch part cost, but greatly reduce cooling requirements and filter costs.

Problem: Cost is a major issue – an order of magnitude reduction is needed.

Power Switches

Power switch costs need to be reduced from about $100 per switch (600 amp, 600 volt Toshiba fourth generation Insulated Gate Bipolar Transistor, IGBT) today to about $5.00 per switch for a commercial power controller. Current manufacturing technology is expected to attain only about $14.00 per switch with high volume production (million quantities). Improved manufacturing and switch technology has led Harris engineers to estimate that a prototype 500 volt 200 amp switch might approach the $5.00 per switch goal in a PEBB configuration.

Passive Devices for High Speed Switching

High power density, low-loss capacitors and inductors are needed for high speed switching in electric power applications. The total cost for filter and boost/buck components must be less than $50.00 per 100 kW system. Passive devices require basic materials research to isolate materials with high power density and low losses for high speed switching in electric power systems. Magnetic materials development is mostly centered on motor metals, but emphasis is needed on the inductor materials as well.

Controls and Topologies for Advanced Power Systems

Flexible, software based, nonlinear control schemes must consider other nonlinear components in the system while adding only a few dollars to the system cost. This should be achievable in mass markets with standardized control schemes. Power topologies such as soft-switching, improve bulk power conditioning efficiency by removing switching losses in the power devices. Soft-switching greatly improves low end motor controller efficiency and is ideal for all high speed, high power, conditioning technologies where efficiency and cool running is vital.

Labor Needs to be Process Oriented

Labor accounts for a large amount of the cost in any inspection driven process. Highly skilled engineers and technicians are required at many levels during fabrication of power electronics. To complicate alignment, each converter or controller tends to be unique due to its parasitic capacitance and inductance. This uniqueness requires an expensive, inspection driven quality control system. Fabrication of power conditioning equipment needs improvement to overcome the uniqueness of each controller. This is done by reducing the scale of the components to a point where the parasitic effects have little effect on alignment. An automated process can assure quality control with the technician monitoring the process and not the product.

Power Devices Reliability

Power semiconductors can have extremely long lifetimes if the circuits are designed properly. Fault tolerance and protection circuits are proven methods that lead to long periods between failures. Integrated device design can protect the power device through limits imposed in processing.

Passive Device Parts Estimate for PEBBs

The passive devices will likely cost about \$1.00 per kilowatt, or about another \$100. However the electrochemical capacitors of today were designed to filter stable loads like computer power supplies. These capacitors have short lifetimes when transient loads are applied and tend to be very large relative to the system. Research is necessary for a solid state capacitor with higher performance and reliability. Additionally, new methods to reduce cost are required.

Materials, Processing and Device Technology

Enabling technology for the power switching devices is the KEY to high performance power electronics technology for all light and heavy vehicles. The PEBB is the driving technology for all power electronics technology because it integrates control, high performance architecture, fast switching, and high power density power devices for local and system wide level control. This approach allows both mass production and customization through software for nearly all low, medium and very high power applications.

The PEBB is the enabling technology for electric advanced heavy and light vehicles. Similarly, the power device is an enabling technology for the PEBB. Fast switching power devices provide improved signal with lower total harmonic distortion in the distribution bus and other machine or system components. Other PEBB objectives are decreased parasitic power loss in the form of heat, reduced system engineering and compact components as well as greater system and component reliability. However, to achieve these results, new device designs (in silicon) are required, and/or new higher efficiency electronic materials need to be developed. To support development of both device technology and new materials such as Silicon Carbide (SiC) and GaN, will require extensive work in the science and technology of materials, device fabrication, processing technology and device technology.

Silicon materials, processing and device technology for power switching devices have a learning curve similar to that of dynamic random access memories. Data memories and components are planar structures with planar analysis. Power devices have three dimensional structures; their high power density introduces electric fields and thermal boundaries that distort the fields introduced by traditional doping and control surfaces. Three dimensional analysis is required to properly design power devices. This requires a better understanding of the physics and materials involved. The engineering literature on power devices states that nearly 10,000 switching power devices have been described. However, there are but three general categories of devices in use or anticipated use: the low power planar DMOS that is in commercial production by many IC companies; the IGBT, Integrated Gate Bipolar Transistor, that is used in the Chrysler Patriot, and the MCT, <u>M</u>etal Oxide Semiconductor <u>C</u>ontrolled <u>T</u>hyristor, to be used in the future high speed switching power applications.

Problem: Materials are a major issue - new materials and advanced processes are needed.

Just as it has taken INTEL 15 years to produce a Pentium, it will require mastering a number of technology hurdles to achieve a fully functional power module for hybrid vehicles. Pentiums may appear easy to fabricate but they do not cost \$5.00 / cm^2. The goal of manufacturing a high performance power switching device for the above mentioned cost requires several significant science, technology and manufacturing breakthroughs to occur. Specifically, over the aggressive time frame of the PEBB program, a new dielectric must be developed that has ZERO defects over one sq. cm of active area. Three dimensional (3-D) structures must be designed, created, tested and then miniaturized by 30% within 18 months. The structures must be shrunk again by 30% in order to increase switching speed and current density, i.e. power; containment of the voltage within the device. Development of fast turn off technologies will further increase switch speed and reduce parasitic power loss.

The principle objective of the silicon technology thrust is to identify the processing, fabrication, device and manufacturing issues that will improve MCT reliability, performance and manufacturability by addressing these issues jointly with experienced members of the IC industry, Government laboratories and the academic community. The assembly of these resources has by no means been completed, nor are the outlined issues solved.

Capacitors Need New Materials

Capacitors are by far the most limiting device in a power application's lifetime. New materials are needed to overcome this limitation. The DOE has a small program to develop, so called "Super Capacitors" or "Ultra Capacitors," but these capacitors do not support high speed switching. DARPA and the Air Force have similar capacitor programs following different materials, but these also make poor filter elements. DOD and DOE are searching for ways to include filter capacitors into their programs.

The solid-state, nanostructure capacitor like the one developed at Lawrence Livermore National Laboratory -- a spin-off from turbine blade material research -- is needed. Work is needed to develop processing techniques for these capacitors to achieve the low cost goals indicated above.

Advanced Materials Technology for Beyond 2000

A new generation of materials has matured to where simple device structures have been fabricated and the promise of their properties makes GaN and SiC technology both exciting and practical. Unfortunately, the principal investor for these wide band gap technologies is DOD, and except for some LEDs, there are no commercial products to support the technology. Both large corporations such as Westinghouse and small startups such as CREE have begun investing in this technology for power switching devices, but only at the urging of DOD program personnel.

The promise of this technology is incredible; due to the wide band gap of these semiconductors, the breakdown voltage of SiC is 10 times that of Silicon (Si) making the thickness requirement for a power device smaller by that factor. Due to the higher current density, the power device can be miniaturized from one square centimeter to two millimeters on a side or less. Switching speed will also improve. Transportation uses for these materials include reduced system complexity by eliminating liquid cooling of the electronics and higher voltage switches for high voltage storage systems like capacitors and flywheels.

The issues are that these materials are immature; although a delight and a challenge to material scientists, device and process engineers as well as solid state physicists and chemists. As a practical matter, no one but the government will invest in these materials for the near term.

Summary of Major Technical and Economic Challenges

Active power components are similar to their computer cousins except that their planar flow and high current density introduce field distortions in the device. This forces a much better understanding of the device's material properties and greater emphasis on the physics in manufacturing technology. A great deal of cost reduction is necessary for electric propulsion applications.

Passive components need to be redesigned with power applications in mind. Research in new materials is needed to extend life and improve performance.

Interconnection devices for transportation power systems need to be light, compact, efficient and reliable. The nut, bolt and terminal approach need to be eliminated to reduce cost. New connection strategies are necessary for general purpose power controllers.